

Review Paper

Hydrogen-induced Fuel System in RCCI Engine for Clean Combustion: A Review

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Abstract

Research in the field of internal combustion engine using environmentally friendly fuels must be the main focus to increase efficiency, engine performance, reduction of exhaust gas emissions to clean combustion. Reactivity Controlled Compression Ignition (RCCI) on the diesel engines can be used as an innovative solution to increase thermal efficiency and reduce emissions through bending of fuels with different reactivity. This paper presents a comprehensive review of hydrogen-induced fuels systems on RCCI engines, as well as its impact on engine performance, emissions to Clean Combustion. Various studies show that mixing hydrogen in RCCI engines can increase thermal efficiency, speed up the combustion process, and reduce nitrogen oxides (NO_x), particulate matter (PM), carbon monoxide (CO), hydrocarbons (HC) and Smoke Opacity emissions. This review provides insight into the trend of development of hydrogen-induced RCCI on diesel engines and its prospects in realizing a clean and efficient combustion system, so that future research focus is important for finding appropriate fuel mixtures, operating parameters, and choosing optimal engines by considering technical problems, thermodynamics, economics, and the environment, as well as exploring the potential implementation of this technology in the future.

Keywords: Hydrogen; RCCI; Diesel engine; Engine performance; Clean combustion

1. Introduction

The more efficient and environmentally friendly energy needs have become global concern in facing the challenges of climate change and scarcity of fossil energy resources [1]. To replace fossil fuels and reduce harmful emissions, alternative fuels must be found [2], [3]. The transportation and industrial sector, which is widely dependent on diesel engines, contributes significant portions in carbon dioxide emissions (CO₂) and other pollutants [4], [5]. Diesel engines, despite having high thermal efficiency, are known as one of the main sources of Nitrogen Oxide emissions (NO_x) and particulates [6], [7], [8] which

have a negative impact on the environment and human health. Therefore, research to improve the efficiency of diesel engines while reducing harmful emissions continues to be carried out intensively including using the Reactivity Controlled Compression Ignition (RCCI) technology [9], [10].

In practice RCCI uses a dual fuel model which is two types of fuel with different reactivity, namely low reactivity fuel for initial mixing and high reactivity fuels that are injected directly into the cylinder before the combustion process [11]. In the review of this article discussed the use of hydrogen fuels in RCCI/Diesel engines as



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alternative fuels that offer solutions to increase efficiency and clean combustion [12], [13]. The combustion characteristics of hydrogen in terms of combustion efficiency, power output, NO_x emissions, and thermal efficiency show that the combustion efficiency and power output performance are higher, this condition causes hydrogen to increase the combustion reactivity and accelerate the flame propagation [14], [15], [16]. On the other hand, the case of ammonia shows a slightly lower thermal efficiency than hydrogen, making hydrogen a more efficient fuel overall in terms of internal combustion engine performance, as shown in **Figure 1**.

The use of hydrogen-induced fuel in diesel engines cannot be separated from technical challenges [17]. Increased NO_x emissions due to higher combustion temperatures, knocking risk, and the need for precise fuel injection and fuel control technology is the main obstacle in the development of a hydrogen-induced dual diesel engine. Knocking is defined as the presence of an abnormal sound or knocking from the combustion chamber when the engine is operating due to incomplete combustion, low octane, carbon deposits and incorrect ignition timing which causes engine performance to decrease [18], [19], [20]. In addition, the availability of hydrogen infrastructure and the cost of hydrogen production is also an important factor that needs attention [21], [22]. Hydrogen is a gas material that is free of carbon, so it becomes an excellent alternative for conventional fuel. On the other hand, there are some deficiencies and benefits of hydrogen when used as conventional fuel in automotive engine systems. In a study, it is always measured how the formation of carbon monoxide (CO), carbon dioxide CO₂, non-burning hydrocarbons (HC), and NO_x on the diesel engine of ignition direct ignition of turbocharged water-cooled water-cooled four-cylinder with recycling fuel [23], [24], [25], [26]. However, there is another way to reduce NO_x without reducing its performance, namely by adding an exhaust gas recirculation (EGR). Among the suggested solutions is to use hydrogen fuel, which is still abundant and has not been utilized for internal combustion engines [27], [28], [29], as shown in **Figure 2**. At this juncture, the aspiration to harness cleaner and more sustainable energy sources is increasingly prevalent, driven by a multitude of

needs. Industrialized countries have realized noteworthy advancements in the transformation of their energy requirements from conventional sources to renewable and environmentally sustainable non-conventional energy sources.

The combustion mechanism of hydrogen-induced fuel diesel engine reveals notable distinctions when analyzed against conventional diesel fuel, as the combustion of the pre-mixed fuel in the dual fuel operational mode is considerably shaped by the combustion phase of the pilot fuel [30], [31], [32]. as represented in **Figure 3**. Furthermore, the differences between dual fuel and single diesel operational modes are depicted in **Figure 4**, indicating that both single fuel and dual fuel combustion modalities encompass three fundamental stages, namely turbulent mixing, the initial phase (low-temperature chemical volumetric activation), and the subsequent phase (high-temperature chemical volumetric activation at the spray tip) [33], [34]. In

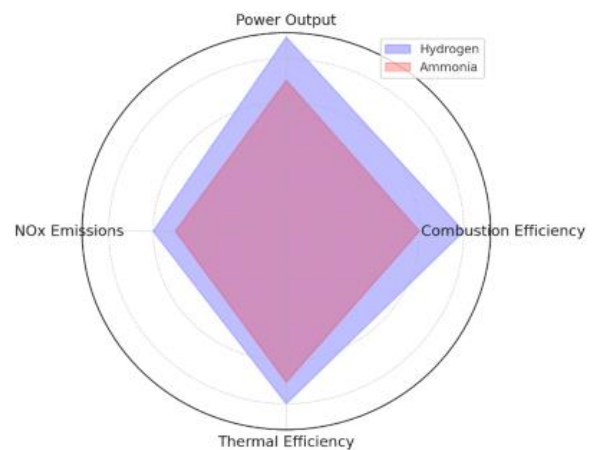


Figure 1. Combustion characteristics of hydrogen and ammonia [15], [35]

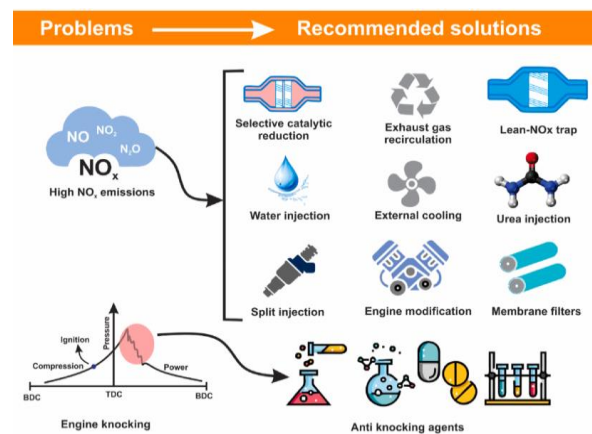


Figure 2. Hydrogen-based problems and solutions in internal combustion engines [36]

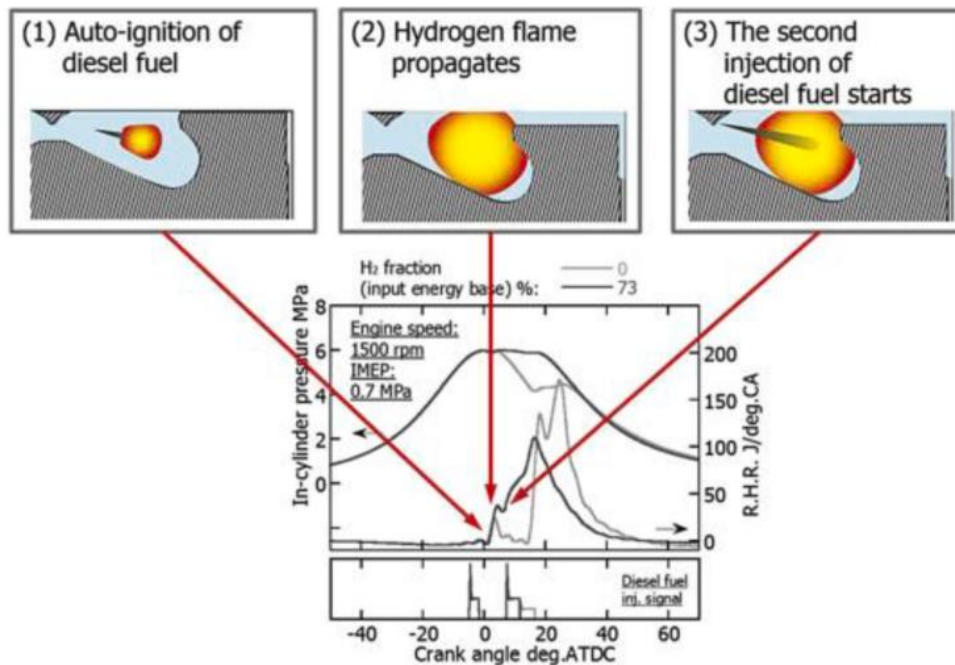


Figure 3. Dual fuel combustion type (hydrogen-diesel) with a single diesel engine [37]

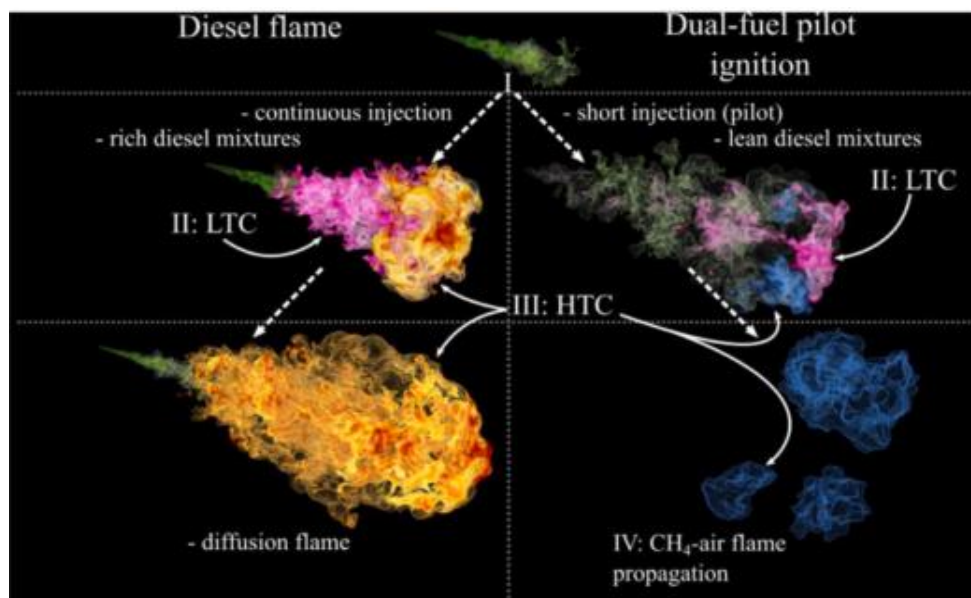


Figure 4. The differentiation between single diesel combustion modality and dual combustion mode utilizing gaseous fuel, specifically represented by methane (CH_4). Low temperature chemistry (LTC), and high temperature chemistry (HTC) [34]

contrast to the single fuel spray, where high-temperature ignition is sustained by a markedly luminous quasi-stable diffusion flame [38], [39], [40].

Gas-powered internal combustion engines fundamentally function based on principles analogous to those employed by gasoline-powered engines (utilizing either carburetor or injection systems) and diesel engines, which encompass both four-stroke and two-stroke

configurations [41], [42], [43]. The foundational architecture of the combustion engine remains invariant; however, it is the specific type of fuel employed and the associated systems that serve to differentiate these engines [44], [45]. Critical prerequisite for all combustion engines is that alterations in fuel type do not modify the operational cycle of the engine itself [46], [47]. For instance, in an engine engineered for a four-stroke cycle, substituting gas fuel will not alter its

adherence to the four-stroke operational framework [43], [48].

This paper aims to provide a comprehensive review of the latest developments in the research and development of dual diesel engines with hydrogen-induced fuel. The discussion includes the working principle of dual-fuel diesel engines, the impact of the use of hydrogen on efficiency and emissions, technical challenges. Thus, it is hoped that this review can be a reference for researchers, practitioners, and policy makers in encouraging their application directly in the future.

The motivation of the author in studying related to this literature is due to the development of the automotive industry which increasingly needs innovation, both used in industry, transportation, agriculture and others, especially in the use of environmentally friendly alternative fuels that are specific to diesel engines. The search and composition of fuel on diesel engines in producing perfect efficiency must be carried out continuous studies to obtain maximum results until the conditions are ready to be applied significantly in the internal combustion engine. The development of renewable gas fuel engines has become an important step for the development of green environmental protection projects throughout the world.

2. Methods

This research was conducted using a qualitative method through a literature study on dual fuels using hydrogen in diesel engines for clean combustion as well as improving combustion and engine efficiency. The article search was carried out by taking from the ScienceDirect database for the last 15 years, starting from 2011 to March 2025, as well as using the scopus database with a total of 9,689 articles obtained. The identification of articles in the writing of this review paper was obtained through the scienceDirect database, which is as many as 9,664 articles over the last 15 years starting from 2011 to March 2025 with the search keyword "Dual-fuel diesel engine with hydrogen as fuel gas" and some are also taken from the scopus database with the number of 25 articles that have been previously taken manually, So that the total number of articles is 9,689. In this review paper, it is easier to summarize articles made or presented

with the PRISMA diagram method to make it easier to understand the content of the article as seen in [Figure 5](#). PRISMA diagrams function as visual instruments that facilitate the explanation of information flows and significant phases in the process of systematic review of scientific composition, either regarding the evaluation of papers or research articles [49], [50]. In the PRISMA application, diagrams are designed to assist authors in articulating systematic reviews and meta-analyses in clear, comprehensive, and transparent manner, thereby improving the reader's understanding of the research methodology presented in the scientific paper [51], [52].

The presentation of articles that are used as objects of review analysis as seen in [Figure 1](#), where the total number of articles is 9,689 where the number has not been selected based on 4 focus categories of material in the desired field of needs in this review paper, namely (1). Hydrogen-Diesel Dual Fuel Engine; (2). RCCI Engine; (3). Clean Combustion and (4). Dual Fuel Performance. In principle, from the total number of articles that have been obtained, then articles that are not included in the focus field category are eliminated or filtered based on several considerations, such as articles that do not discuss abstract results, technology or to conduct non-standard experiments, Conclusions of the discussion results are inconsistent, the properties of the fuel used are not in the contents of the article, the research methodology is not relevant to dual fuel gas and liquid, using two languages or more in the article, does not discuss combustion performance and the most does not provide discussion and about the effects of gas emissions after being carried out. Furthermore, from all the articles obtained, 142 articles have been filtered, which number is used for the review analysis paper with the hope of obtaining the latest information related to trends and developments in research on dual-fuel diesel-hydrogen engines to be used as a reference in subsequent research as an alternative fuel in the automotive sector.

Summary of the number of selected articles from the selection results, namely 142 article titles taken and selected based on the discussion field category, are shown in [Table 1](#). namely the hydrogen-diesel dual fuel engine category; RCCI engine; clean combustion and performance dual-

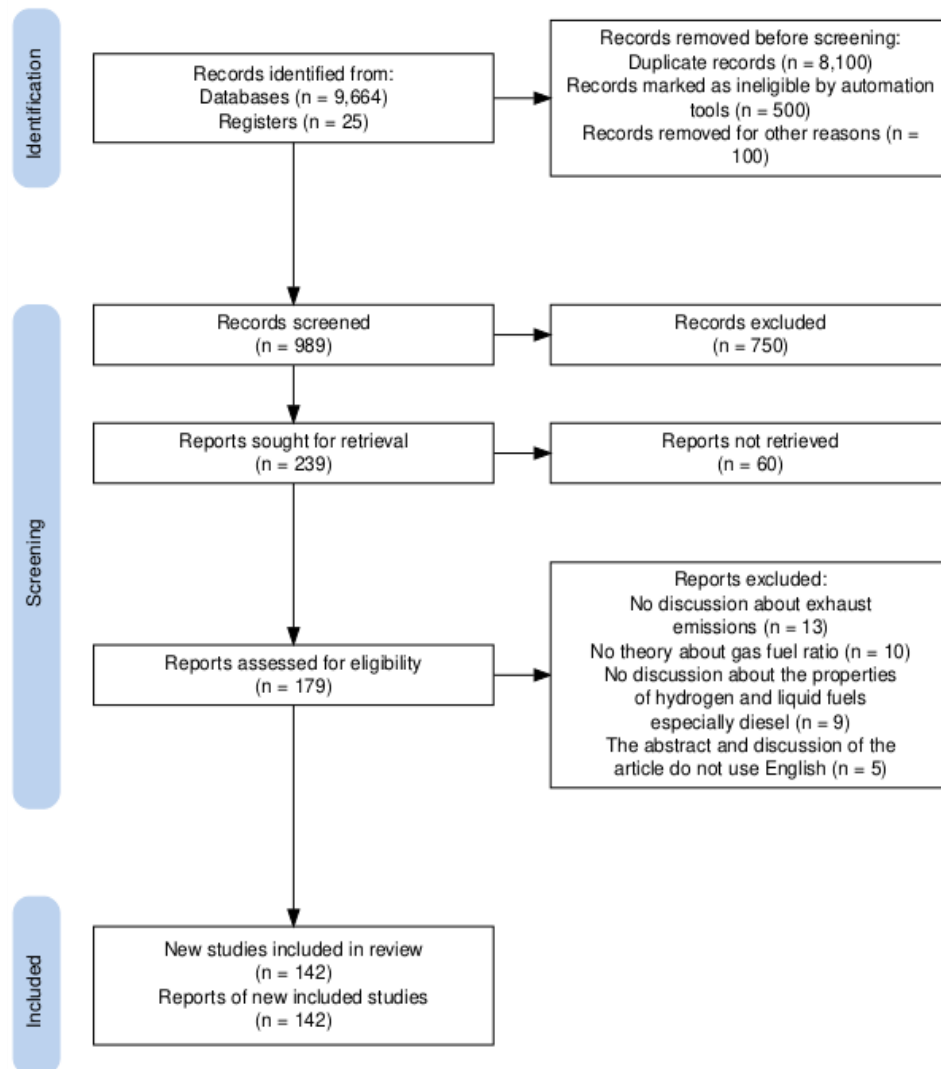


Figure 5. PRISMA diagram in article collection method

Table 1. Focus category of article search in reputable databases

Search article focus category	Number of Articles
Hydrogen – Diesel Dual Fuel Engine	57
RCCI Engine	41
Clean Combustion	19
Performance Dual-Fuel	25

fuel taken from internationally reputable databases, namely sciencedirect and scopus. **Table 1.** provides information that the focus field on the hydrogen-induced Diesel dual fuel engine category occupies the largest number of articles obtained, as many as 57 articles, all of which are indexed in reputable international journals, while for clean combustion, it occupies the smallest number, namely 19. From **Table 1**, information can be obtained that there is still potential for further

research related to dual-fuel hydrogen in diesel engines that focus on the 4 (four) categories. Hydrogen induced in diesel engines is one of the most interesting research topics for innovation, both in terms of technology, fuel and clean combustion to zero combustion which is currently an issue for society and even countries in the world in resolving the issue of environmental impacts from combustion that produces free carbon.

Figure 6 is the development or trend of articles that have been published by researchers who focus on the combustion engine field with various research phenomena that are pursued with 4 search focus areas, namely (1). Hydrogen-Diesel Dual Fuel Engine; (2). RCCI Engine; (3). Clean Combustion and (4). Performance Dual-Fuel, the selection results from the search produced 142 articles that were used for the analysis of literature

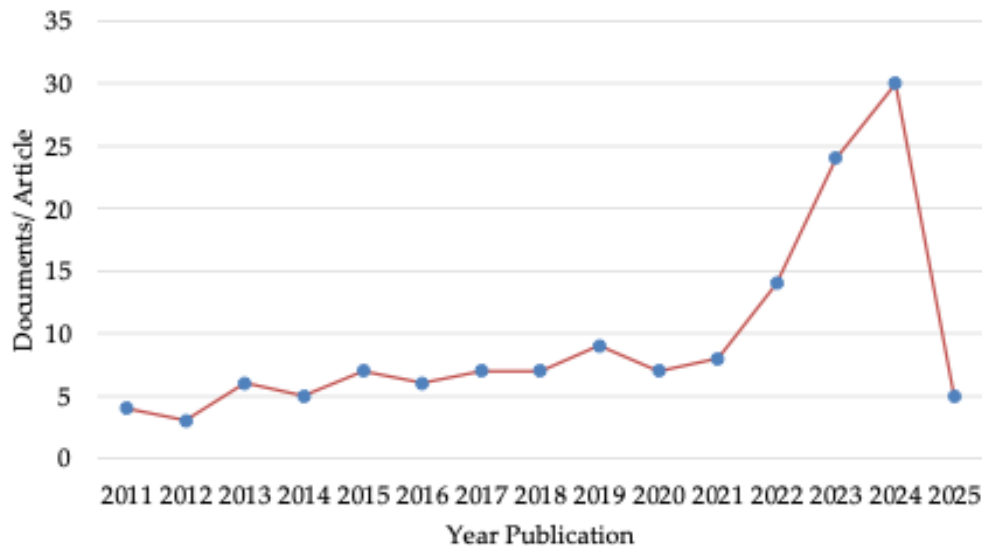


Figure 6. Publication development using hydrogen fuel in diesel engines 2011-2025

studies in this paper review. The publications displayed start from 2011-2025 and are equipped with the large number of articles produced each year, where in [Figure 6](#) it can be seen that since 2011 there have been 4 publications produced but then decreased in 2012, overall in [Figure 6](#). informs that the average trend of publications continues to increase until 2024, although in some years there also appears to be no increase in the number of publications but tends to remain the same as in 2017 and 2018. The search keywords by creating 4 focus areas actually reflect the research needs that can be developed more specifically or can combine these focus areas with the main theme being combustion in internal combustion engines on hydrogen-induced fuels that produce high efficiency and zero carbon.

Publication of articles is an important part of the reference material in this literature study, because by collecting internationally credible reference sources, the results of the review paper can provide more up-to-date information, both research development trends, methodologies used, theoretical and simulation approaches, test equipment used and the latest technology in the research being carried out, where all of that is the most important part of the information that needs to be obtained. [Figure 7](#) is the type of article that has been obtained from the results of the selection of 142 articles, the writing has been published by several researchers from 2011-2025, which is divided into 3 types of acquisition, namely research articles, review papers and conference papers. The results of the selection of article types

from the sciencedirect and scopus databases obtained with the highest percentage are research articles or original articles from laboratory tests or simulations, namely 105 (74%) of the total 142 articles and the second place is obtained by the review paper type, namely 25 (18%) with various study themes related to dual fuel in diesel engines, especially on the use of fuel such as the addition of helium, liquid petroleum gas, biogas, which means that there are still not too many articles that conduct studies related to the theme of hydrogen mixing in diesel engines, so that the opportunity for a review is still open. In [Figure 7](#) it can also be seen that publications in the form of conferences appear as much as 8% which informs the smallest percentage of the total publication model produced in the period from 2011-2025. Discussion related to [Figure 7](#) can be said that several types of references inform the percentage that can be developed, because the trend of research development is still widely discussed with the big theme being efficiency and clean combustion in internal combustion engines.

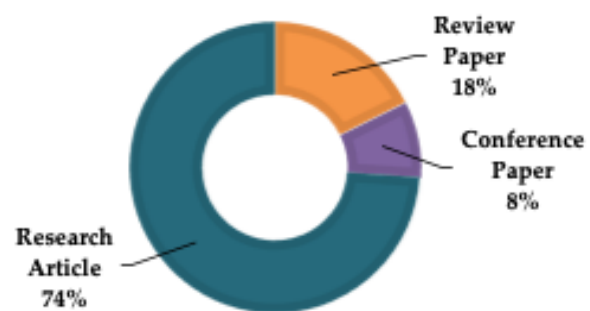


Figure 7. Types of articles published from 2011-2025

The next method in this literature study is to look at the trend of articles published by researchers in reputable international journals or in international conferences indexed by the Scopus database. **Figure 8** is the percentage of publications conducted by researchers in reputable journals or publishers with an average indexed by Scopus quartile 1, where the most publications are in the international journal of hydrogen energy, which is 36% and the second most publications are in the Fuel journal 26% while the others as seen in **Figure 8** are the highest 7%. Based on the percentage of the number of articles published in reputable journals, it provides the view that the field of research related to internal combustion engines, especially those researching fuel, is more appropriate to be published in the international journal of hydrogen energy because it is in accordance with the research theme and the name of the journal being targeted and the citations or references of researchers who focus on the field, in addition, if the specific research developed is on the general fuel aspect, it is more appropriate to be published in the Fuel journal, while other themes can be adjusted to several journal publishers that have a percentage of 7% or below while still paying attention to the suitability between the research theme and the intended publication location.

Figure 9 informs the spatial distribution of articles published on dual fuel hydrogen-diesel engine research in different countries. According to **Figure 9**, the countries with the highest number of publications are as follows: India (19 articles, 20%), China (14 articles, 15%), Malaysia (12 articles, 13%), Japan (9 articles, 10%), and the United States/Turkey (8 articles, 9%). These five countries, ranked first to fifth, are leading in research in the field of dual fuel hydrogen-diesel engines, indicating that the majority of leading research groups and practitioners are concentrated in this field. This research trend from various countries still has the potential to be developed further, hopefully carried out through collaboration between researchers in other countries, so that a research climate or atmosphere can be created that can support its implementation in the form of commercialization of research results to be applied in actual conditions after passing experimental tests.

3. Results and Discussion

Hydrogen is regarded as the most viable alternative energy resource for supplanting traditional fossil fuels, attributable to its renewable and ecologically sustainable characteristics [53]. Hydrogen does not occur naturally in either its elemental or molecular state;

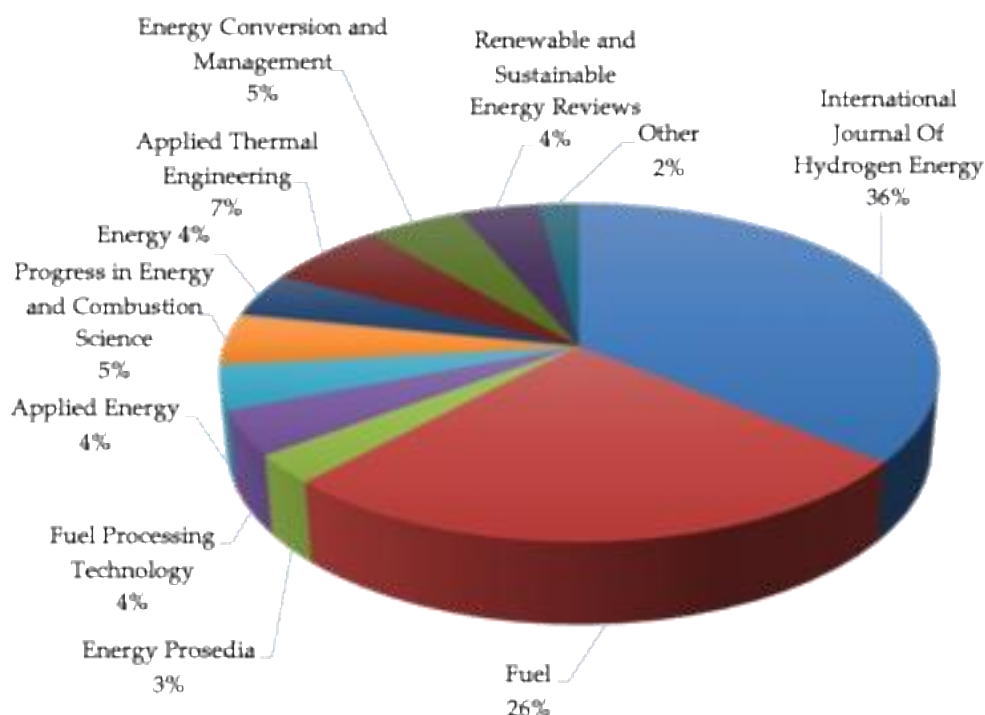


Figure 8. Percentage of publications from reputable publishers 2011-2025

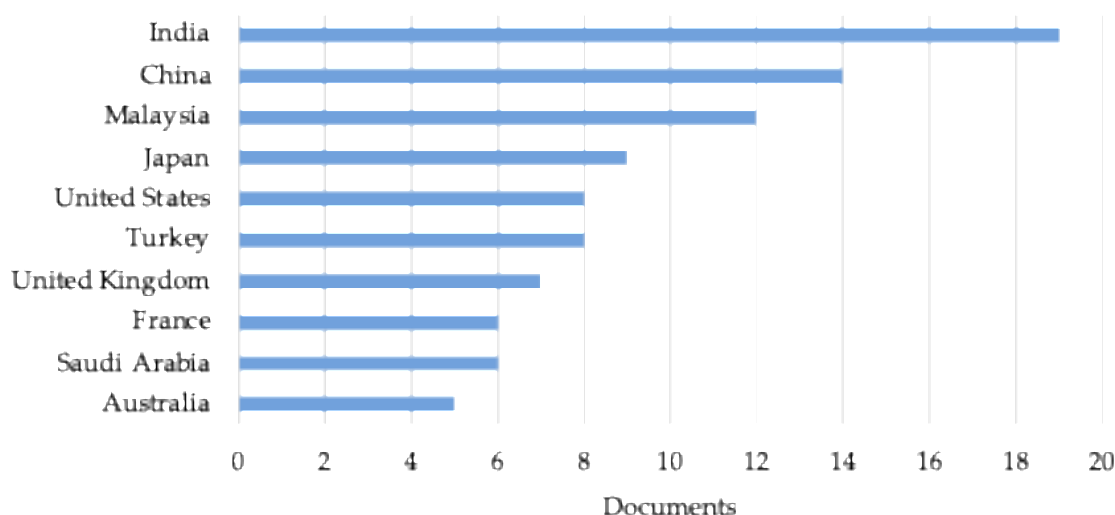


Figure 9. Number of publications from several countries from 2011-2025

rather, it necessitates additional extraction from a variety of compounds [54]. The properties of low density and viscosity associated with hydrogen are critical factors that influence its presence in a gaseous state. In light of economic considerations, the majority of hydrogen production is predicated upon hydrogen-rich compounds, including fossil fuels [55], [56].

The mechanism of hydrogen induction encompasses the incremental infusion of hydrogen into the combustion chamber, thereby augmenting the reactivity of the fuel mixture and facilitating low-temperature combustion [57], [58]. This phenomenon may result in diminished emissions and enhanced efficiency within RCCI engines, thereby aligning with objectives of sustainable transportation [59], [60]. Furthermore, the incorporation of hydrogen promotes superior mixing with the primary fuels, culminating in a more uniform charge that improves ignition characteristics and combustion stability. This ultimately yields a reduction in NO_x and particulate emissions when juxtaposed with traditional diesel operation. Additionally, the hydrogen induction mechanism can assist in alleviating issues pertaining to combustion knock and enhance overall engine performance by accommodating a broader spectrum of operational conditions [61]. The effective realization of hydrogen-induced fuel systems in RCCI engines could potentially catalyze substantial advancements in clean combustion [57].

Figure 10 shows the injection method or technique in the combustion process for several

fuel properties [62]. the direct injection method facilitates fuel delivery subsequent to the closure of the intake valve, thereby mitigating the risk of backfire due to the rapid dispersion and amalgamation of hydrogen and air. Upon the closure of the intake valve, the low-pressure direct injector introduces the primary fuel (i.e., hydrogen) when the internal cylinder pressure is at a reduced level. Conversely, the high-pressure direct injector administers the pilot fuel (i.e., diesel) at the conclusion of the compression stroke. It is noteworthy that the designation “low-pressure” pertains to the direct gas injector that supplies the primary fuel (i.e., hydrogen) at a comparatively lower pressure than that of the high-pressure injector, which dispenses the pilot fuel [63].

Direct injection confers substantial advantages, even when hydrogen is injected at earlier crank angles, due to its refined control over the timing, duration, and volumetric quantity of fuel introduced into the combustion chamber [64]. **Figure 11** shows the development of combustion phenomenon in a hydrogen-induced fuel diesel engine near top dead center (TDC), the stages in the injection process are clearly visible in the colors shown in the illustration. Compared to carburation and port injection techniques, direct injection produces a more homogenous air-fuel mixture because of the increased turbulence in the fuel-air stream caused by the high injection pressure [65]. Direct injection produces a more uniform air-fuel mixture than port and manifold injection techniques because it allows for precise control of the timing, duration, and quantity of

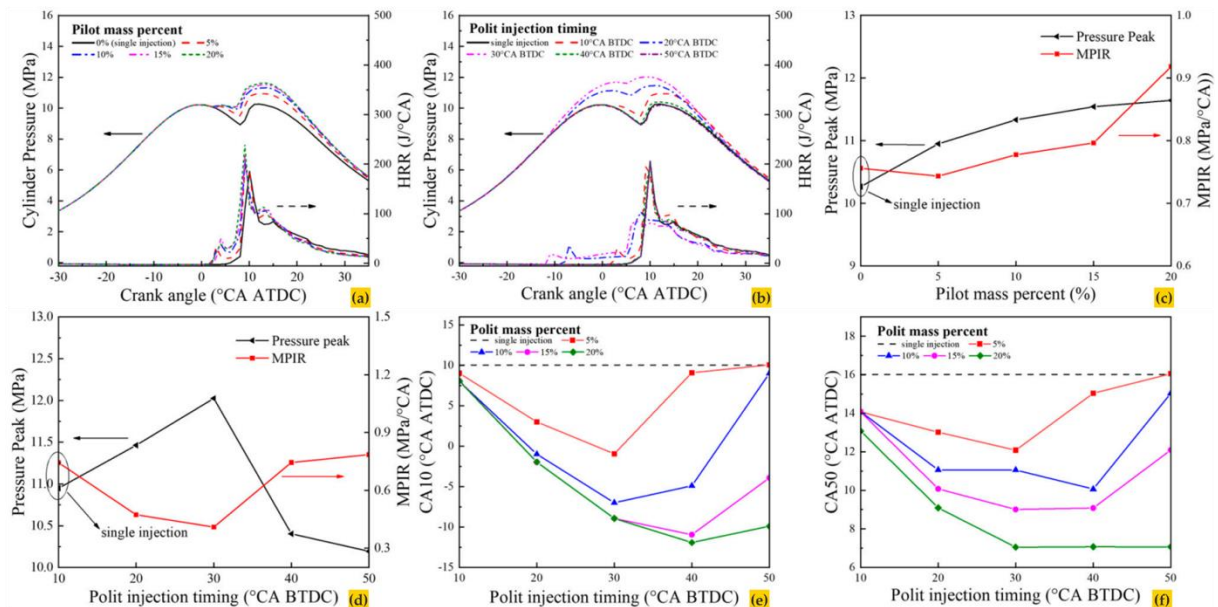


Figure 10. Comparative injection techniques on the combustion properties: (a) Pressure in the cylinder and various pilot mass %; (b) Pressure in cylinder and various pilot injection timings; (c) Pressure peak and pilot mass %; (d) Pressure peak pilot injection timings; (e) Crank angle 10 degrees under different pilot mass % and timing of pilot injection; (f) Crank angle 50 degree under different pilot mass % and timing of pilot injection [63]

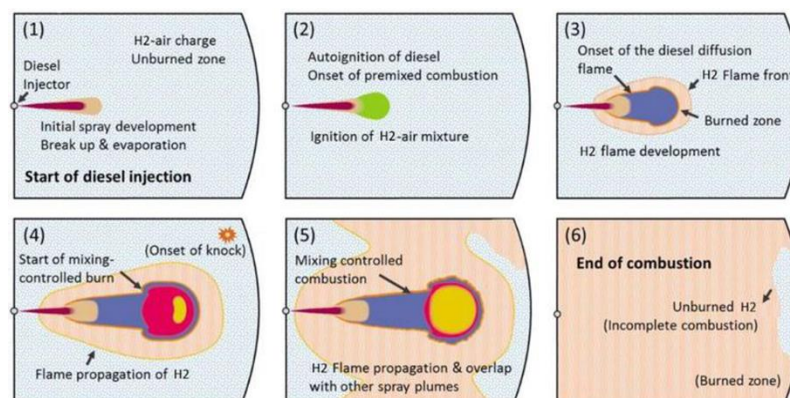


Figure 11. Progression of the combustion phenomenon in the hydrogen- induced fuel diesel engine in proximity to the TDC [66]

fuel injection straight into the combustion chamber [67], [68]. This feature is especially important for hydrogen-induced fuel diesel engines since they require well-mixed, uniformly distributed combination of hydrogen/diesel and air in the combustion chamber [69].

The application of diesel engines is extensive in the realms of transportation, agriculture, and industrial sectors worldwide, chiefly because of their improved energy efficiency, reliability, versatility, and economic merits relative to gasoline engines [70]. The detrimental emissions released by diesel engines heighten the greenhouse effect and create significant risks to human health as a result of the expulsion of nitrogen oxides (NO_x) and particulate matter

(PM) [71], [72]. These emissions are subject to international regulation through the enforcement of rigorous emission standards, as depicted in Figure 12. A multitude of studies have substantiated the assertion that emissions from diesel engines can induce lung cancer and other life-threatening ailments in humans. As result, global emission control policies seek to mitigate PM and NO_x emissions from diesel engines, thereby establishing thresholds for achieving feasible minimum pollutant emissions [73].

Liu *et al.* executed a thorough examination of the impacts of differing engine operational parameters on a dual-fuel engine that utilizes hydrogen as its main fuel [63]. The emissions of CO₂ for each engine load exhibit a gradual decline

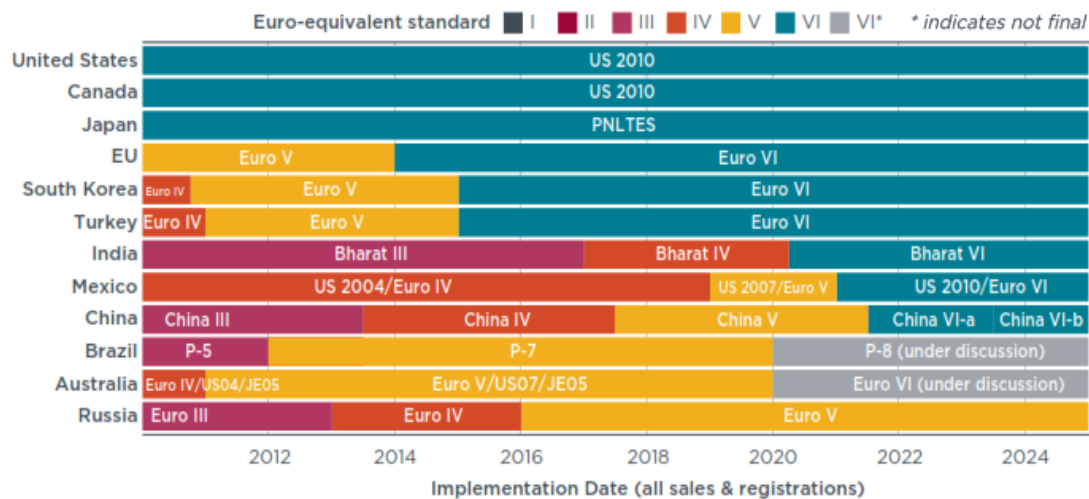


Figure 12. Implementation timeline of heavy-duty emissions standards [74]

as the hydrogen substitution ratio is augmented, as illustrated in Figure 13a. Moreover, CO₂ emissions diminish concurrently with an increase in engine load [63]. Notably, at load conditions of 30%, 50%, 70%, and 90%, the respective average decreases in CO₂ emissions corresponding to rising hydrogen replacement rates are found to be 20.2%, 21.9%, 17.7%, and 9.9%. Figure 13b indicates that while NO_x emissions escalate in high-load scenarios, they experience a decrement in medium- and low-load circumstances. There exists a discernible trend regarding the rate of hydrogen substitution; specifically, NO_x emissions are observed to decline with increasing load. As the hydrogen substitution rate is elevated and the load reaches 70% and 90%, the average increments in NO_x emissions are recorded at 4.54% and 9.53%, respectively. The mean temperature and peak cylinder pressure are noted to decrease with an escalation in the EGR rate, as depicted in Figure 13c. Pertaining to the absence of EGR, the highest cylinder pressure is diminished by 0.5%, 1.7%, and 3.7% in relation to EGR rates of 5%, 10%, and 15%, respectively; concurrently, the

average maximum temperature undergoes reductions of 0.8%, 1.1%, and 2.5%, respectively [63].

Dual fuels in compression ignition (CI) engines, especially the combination of hydrogen and diesel, are increasingly attracting attention in efforts to develop clean combustion technologies and energy efficiency [75]. Conventional CI engines that have been fueled by diesel are now being explored to be combined with hydrogen, considering that hydrogen has the advantages of producing no CO₂ emissions, high calorific value, and fast and clean combustion rates [76]. However, due to the very low cetane number of hydrogen, it cannot ignite itself through compression like diesel. Therefore, a dual-fuel system is used, where hydrogen is mixed into the intake air, and diesel functions as a pilot fuel injected near the top dead center (TDC) to initiate combustion. Several experimental studies have shown that this system can significantly reduce diesel consumption, even more than 50%, and increase thermal efficiency by up to 15% under certain

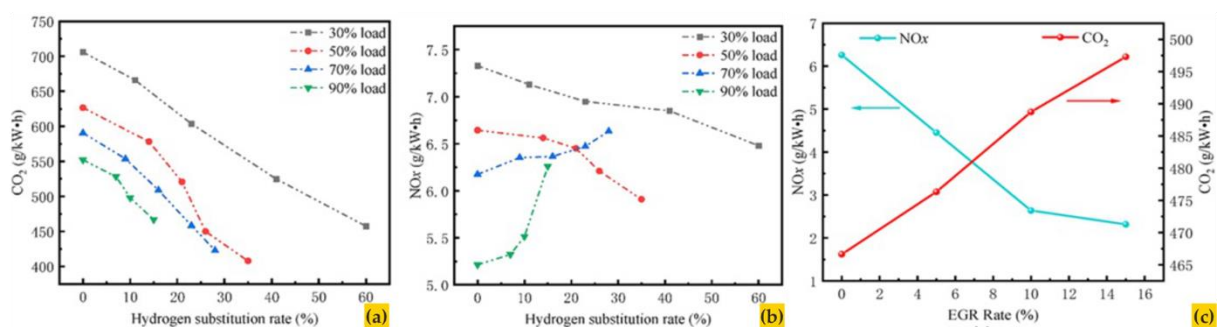


Figure 13. Effects of: (a) hydrogen substitution rate with CO₂; (b) hydrogen substitution rate with NO_x; (c) EGR rate with CO₂ and NO_x [63]

conditions. Exhaust emissions such as CO₂, HC, and CO also experience a significant decrease [77], [78], as seen in the summary of the investigation review **Table 2**.

3.1. Hydrogen-induced Fuel System in RCCI Diesel Engine

In recent years, various sophisticated technical methodologies have been utilized (**Table 3**), highlighting the study of cutting-edge combustion approaches defined by superior thermal efficiency and exceptionally low emission outputs, as explored by academics specializing in the area of internal combustion engines, such as homogeneous charge compression ignition (HCCI) [79], reactive controlled compression ignition (RCCI), premixed controlled compression ignition (PCCI), and dual-fuel combustion [80], [81].

HCCI and Partially PCCI combustion methodologies exhibit numerous advantages, including the concurrent reduction potential of exhaust emissions and elevated thermal efficiency; however, their inherent challenges encompass the regulation of ignition timing, constrained power output, and inadequate cold start performance [82]. Moreover, both HCCI and PCCI combustion methodologies are typically characterized by elevated levels of HC and CO emissions. Conversely, the RCCI technology represents a variant of HCCI combustion technology that employs dual-fuel combustion strategies [83], [84]. Nieman, delineated that this innovative concept can facilitate enhanced combustion control and attain thermal efficiencies nearing 60% in comparison to alternative technologies such as HCCI and PCCI [85].

Table 2. Overview investigations on dual-fuel (hydrogen + diesel) powered CI engine

Refs.	Test condition	Engine characteristics	Engine performance	Emission
[7]	Engine loads (2–12 kg), compression ratio 17.5:1	Single cylinder, 5.7 kW@1500rpm, 661 cm ³ , displacement	BTE ↑; BSEC ↓; BSFC ↓; PCP ↑ at full load	CO ↓; CO ₂ ↓; NOx ↑; Smoke ↓
[86]	Hydrogen supply rate 11%, 17%, 30%, and 42% energy fraction	Single cylinder, 5.2 kW@1500rpm, 661 cm ³ displacement	BTE ↑; BSEC ↓; HRR ↑; PCP ↑	CO ↓; CO ₂ ↓; NOx ↑; Smoke ↓
[87]	Engine loads (20–100%), CR 18.5:1, hydrogen supply rate as 0.2, 0.4, 0.6, and 0.8 LPM	Six cylinder 260 kW@2200 rpm, 11967 cm ³ displacement	BTE ↑; BSEC ↑; BSFC ↑	CO ↓; CO ₂ ↓; UHC ↓; NOx ↓
[88]	Engine speed @ 2200 rpm, CR18:1, hydrogen supply at 0.15, 0.3, 0.45, and 0.6 LPM	Single cylinder, 8 kW, 395 cm ³	BTE ↑; BSEC ↓; BSFC ↓	CO ↓; CO ₂ ↓; UHC ↓; NOx ↓; Smoke ↓
[15]	Various engine loadings (50–100Nm), CR 18.25:1, hydrogen supply at 20 LPM and 40 LPM	Four cylinder, turbocharged, 48kW, 1461 cm ³ displacement	BTE ↑; BSEC ↓; HRR ↑; PCP ↑	CO ₂ ↓; NOx ↓; UHC ↓
[64]	Different engine loading (30–100%), CR 17.5:1, hydrogen supply at 10 and 13 LPM	Single cylinder, engine 5.2 kW 661 cm ³ , displacement	BTE ↑; BSFC ↓; HRR ↑; PCP ↑	CO ↓; CO ₂ ↑; UHC ↓; NOx ↑; Smoke ↓
[89]	Tested at 30% of engine load, speed as 2000 rpm, CR 17.5:1, hydrogen supply rate was 0 to 81% E/E	Single cylinder, 1300 cm ³ displacement	BTE ↓; PCP ↑	CO ↓; UHC ↓; NOx ↓; Soot ↑
[25]	Two speeds of speeds (3000,3600 rpm), engine loads as 3 and 7 Nm, CR 20:1	Single cylinder engine, 296 cm ³ , 3.5 kW@3600 rpm, displacement	BTE ↑; BSFC ↓	CO ↓; CO ₂ ↓; UHC ↓; NOx ↑
[72]	Different speeds of the engine (1500–2500 rpm), various engine loadings (5–25 Nm), CR 20.5:1, hydrogen supply rate as 21.4 to 49.6 LPM	Single cylinder, 677 cm ³ , 10.3 kW@3000 rpm, displacement	BTE ↓; BSEC ↑; HRR ↑; PCP ↑	CO ₂ ↓; NOx ↑; Smoke ↓

BTE – Brake-thermal efficiency; BSFC - Brake specific fuel consumption; BSEC- Brake specific energy consumption; HRR – Heat release rate; PCP - Peak cylinder pressure

The operation of RCCI utilizing primary reference fuels resulted in an extended combustion duration and diminished rates of peak pressure rise when contrasted with HCCI and Partially Premixed Combustion (PPC) [68], [90]. The combustion efficiency of RCCI was found to be the lowest among the three aforementioned strategies when utilizing PRF fuel [91]. However, notwithstanding the relatively low combustion efficiency, the gross indicated efficiency (GIE) of RCCI was marginally elevated due to reduced heat losses associated with the lower peak pressure rise rates [92]. Over the past decade, a variety of fuels with diverse reactivity profiles have been investigated to advance the RCCI combustion methodology, including PODE3/Gasoline [93], Ethanol/Diesel [94], Natural Gas/Diesel [95], Methanol/Diesel [96], Biogas/Diesel, Alcohol/Diesel [97], Isopropanol-Butanol-Ethanol/Biodiesel and Renewable Fuel Mix-Tailoring [98]. Research has shown that natural gas exhibits a longer ignition delay time compared to other conventional hydrocarbon

fuels characterized by low reactivity, such as gasoline, according to findings from earlier scholars regarding the ignition delay time of various traditional fuels, as illustrated in Figure 14. Consequently, the pronounced reactivity disparity between natural gas and diesel fuel may extend the combustion duration and reduce the rate of peak pressure escalation, commonly referred to as diesel knock, in RCCI engines utilizing diesel fuel as the high-reactivity component [68], [99].

3.1.1. Performance of Dual-fuel and RCCI Engines

Notable trend has emerged within the academic sphere to examine the integration of hydrogen with conventional hydrocarbon fuels and renewable energy sources to determine the performance of dual-fuel and RCCI engines [100]. Notwithstanding the myriad advantages that hydrogen presents, empirical studies have indicated that the implementation of hydrogen levels exceeding 10% within an engine may result

Table 3. Several publications papers related to the application of hydrogen and other gases in dual-fuel diesel engines

Refs.	Ignition Source			Admixture of Hydrogen and Other Gases / Liquid Fuels				Gaseous Fuels Containing Hydrogen		Inert Compounds	Effects on the Behavior of Diesel Engines			
	Diesel	Biodiesel	Fuel Additive	Biogas	NG	CNG	LPG	HHO	Syngas	Inert Gas	Combustion	Performance	Regulated Emissions	Unregulated Emissions
[98]	X	√	X	X	X	X	X	X	X	X	√	√	√	X
[101]	√	X	X	X	X	X	X	X	X	X	X	√	√	X
[102]	√	X	X	X	X	X	X	X	X	√	√	√	X	√
[99]	√	X	X	X	X	X	X	X	X	X	X	√	√	X
[19]	√	X	X	X	X	X	X	X	X	X	X	√	√	X
[103]	√	X	√	X	X	X	X	X	X	X	√	√	√	X
[20]	√	X	√	X	√	X	X	√	X	X	√	√	√	X
[22]	√	X	√	X	√	X	X	√	X	X	√	√	√	X
[104]	√	X	X	X	X	X	X	X	X	X	√	√	√	X
[105]	√	√	√	√	√	√	√	√	√	√	√	√	√	X
[81]	√	X	X	X	√	X	X	√	X	X	√	√	√	X
[85]	√	X	X	X	√	√	X	X	X	X	√	√	√	X
[94]	√	√	√	X	X	X	X	X	X	X	√	√	√	X
[106]	√	X	X	X	X	X	X	X	X	X	√	√	√	X
[107]	√	X	X	X	X	X	√	√	√	√	√	√	X	X
[108]	√	√	X	X	X	√	X	X	X	X	√	√	√	X
[109]	X	√	√	X	X	√	X	X	X	X	√	√	√	X
[110]	√	X	X	X	X	X	X	√	X	X	√	√	√	X
[111]	√	X	√	X	X	X	X	√	X	X	√	√	√	√
[112]	√	X	X	X	X	X	√	X	X	X	X	√	√	X
[77]	√	X	√	X	X	X	X	X	X	X	√	√	√	X

x: not-included, √: included

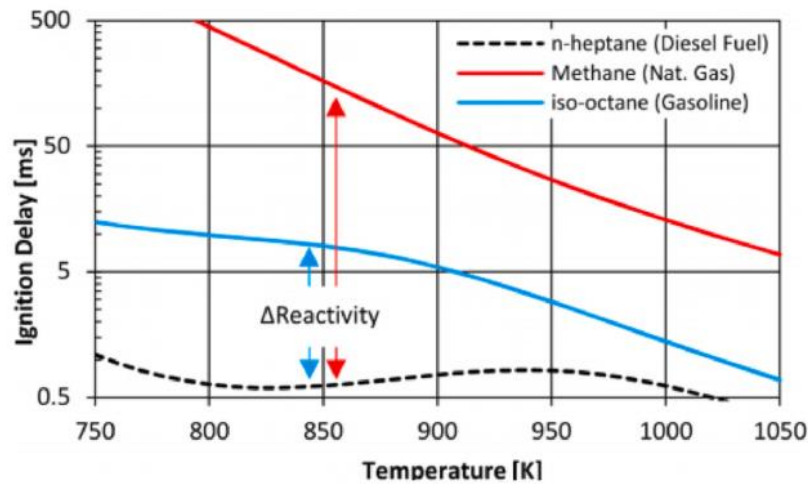


Figure 14. Comparison of reactivity of natural gas and diesel engine fuel with gasoline [85]

in heightened emissions of NO_x [64]. The incorporation of hydrogen fuel may result in a diminishment of the heating value of the fuel-air amalgamation, attributable to the inherently low volumetric energy density of hydrogen, which ultimately leads to reduction in power output under numerous circumstances, although this effect can fluctuate based on various operational parameters of the engine [113], [114]. This phenomenon arises from the comparatively diminished volumetric heating value of the hydrogen-air mixture in relation to that of the natural gas-air mixture, as illustrated in Figure 15, which depicts the enhancement in power output at specified hydrogen concentrations between 10% and 15%. The introduction of hydrogen and hydroxyl radicals can augment the performance of the system, along with the quality and velocity of combustion within the engine; conversely, when utilizing natural gas, its efficacy remains inferior to that of hydrogen, as demonstrated in Figure 16. Furthermore, the performance also hinges on the excess air ratio (λ). Fuwu [115] indicated that when λ is less than 1.2, as evidenced in Figure 16, the enrichment of hydrogen yields a marginal reduction in power output. Conversely, torque experiences a decline in fuel conditions ($\lambda > 1.6$) when employing a compression ratio/CR exceeding 10.5, [115] as depicted in Figure 17.

The rapid combustion velocity of hydrogen results in elevated temperatures and in-cylinder pressures, subsequently leading to an increase in NO_x emissions [7]. This phenomenon can be mitigated by optimizing the mixture to be leaner, leveraging hydrogen's capacity to combust across an extensive range of airborne concentrations

(ranging from 4% to 75%) [116]. The majority of scholarly investigations have established a maximum limit of 15% for the hydrogen enthalpy fraction. The emissions and performance of a

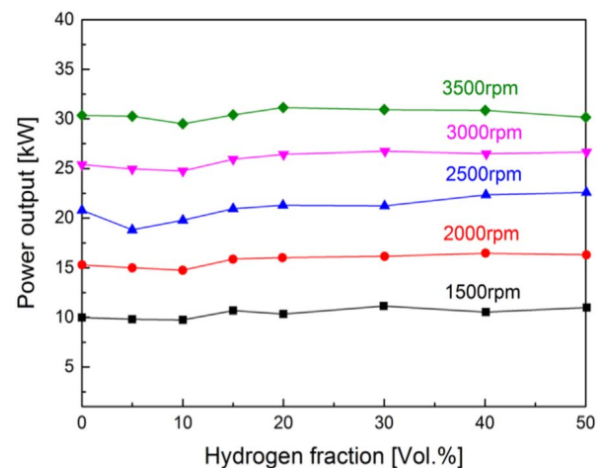


Figure 15. Power measured at the wheels at full load conditions [115]

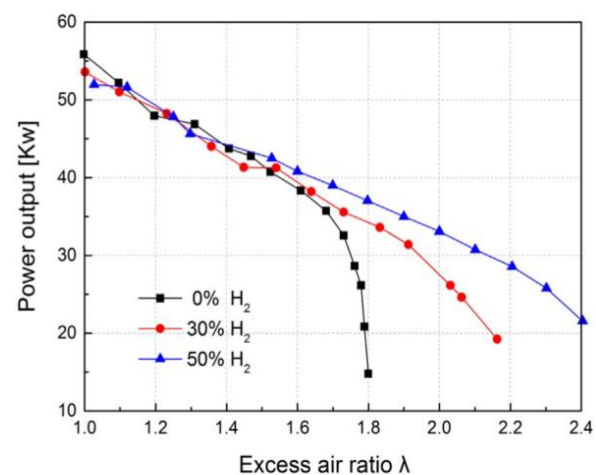


Figure 16. Engine power performance versus excess air ratio and hydrogen fraction [115]

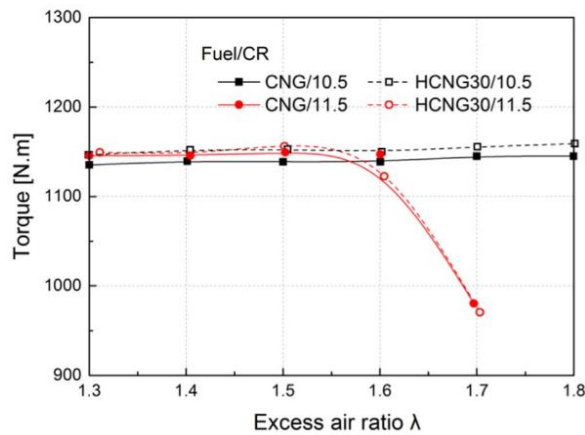


Figure 17. Engine torque performance at lean burn conditions with various CR [115]

naturally aspirated CI hydrogen-induced fuel diesel engine warrant thorough examination at progressively increasing hydrogen enthalpy fractions [7], [43]. Empirical evidence has indicated that hydrogen enhances thermal efficiency and promotes flame stability [117].

Table 4 outlines a detailed assessment of the calorific values related to several fuels characteristically used in both industrial and non-industrial contexts. Among the fuels delineated in the table, hydrogen demonstrates the most pronounced calorific value when appraised through the frameworks of both Higher Heating Value (HHV) and Lower Heating Value (LHV) [26], [118], [119]. Consequently, the potential of hydrogen, which remains underutilized, necessitates immediate application accompanied by comprehensive safety protocols to mitigate any risks associated with its use. Furthermore, the exploration of fuel mixtures to formulate novel fuels remains a promising avenue for development, enhancing the value of combustion applications aimed at substituting fossil fuels [80].

3.1.2. Exhaust Emissions for Clean Combustion

Investigative research indicates that the deployment of RCCI (**Figure 18**), characterized by a hydrogen-diesel fuel amalgamation, can considerably lessen the emissions of carbon dioxide CO_2 , CO, and particulate matter [120], [121]. However, there exists a potential for an increase in NO_x emissions under high engine load conditions if appropriate regulatory measures are not implemented [122]. The use of strategies such as EGR and the modification of fuel injection timing can effectively contribute to the decrease of these emissions [123], [124]. The introduction of hydrogen into RCCI systems has been established to facilitate a marked reduction in unburned hydrocarbons (UHC) and particulate matter emissions [125], a fact that can be mainly attributed to the remarkable combustion properties inherent to hydrogen [4]. Nevertheless, meticulous management of combustion parameters is crucial to mitigate the consequential increase in NO_x , particularly at elevated hydrogen flow rates, thereby necessitating careful equilibrium between operational efficiency and ecological ramifications [101], [126].

Figure 19a illustrates a schematic depiction of the mechanisms that govern the formation of both NO_x and soot in compression ignition diesel engines [127]. Fundamentally, the nitrogen and oxygen available in the atmosphere can partake in a series of chemical reactions, culminating in the production of NO_x in regions that are characterized by elevated temperatures [128]. As depicted in **Figure 19a**, conventional diesel combustion is correlated with heightened emissions of NO_x and particulate matter, attributable to the intrinsic properties of diffusion flame combustion [60]. The adoption of

Table 4. Typical heating value of some fuel [26], [129]

Fuel	HHV [Higher Heating Value, MJ/kg]	LHV [Lower Heating Value, MJ/kg]
Hydrogen	141.89	121
Diesel	44.82	42.5
Gasoline	47.7	44.3
Methanol	20	18
Ethane	52	48.1
Methane	55.8	50
Propane	50.4	46.6
Butane	49.5	45.8
Acetylene	49.9	48.2
Ethylene	50.3	47.2
Coal	5.3	4.4

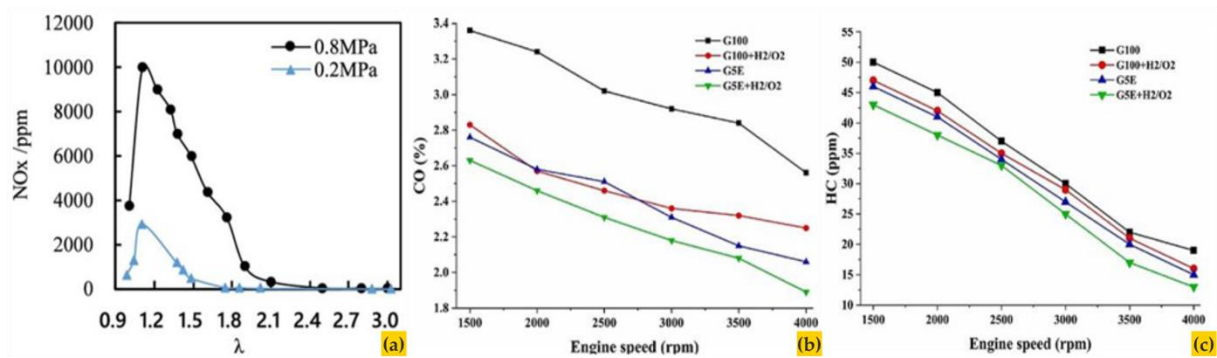


Figure 18. Emission from hydrogen-powered SI engine (a) NOx emission in [130]; (b) CO emission; (c) HC emission [131]

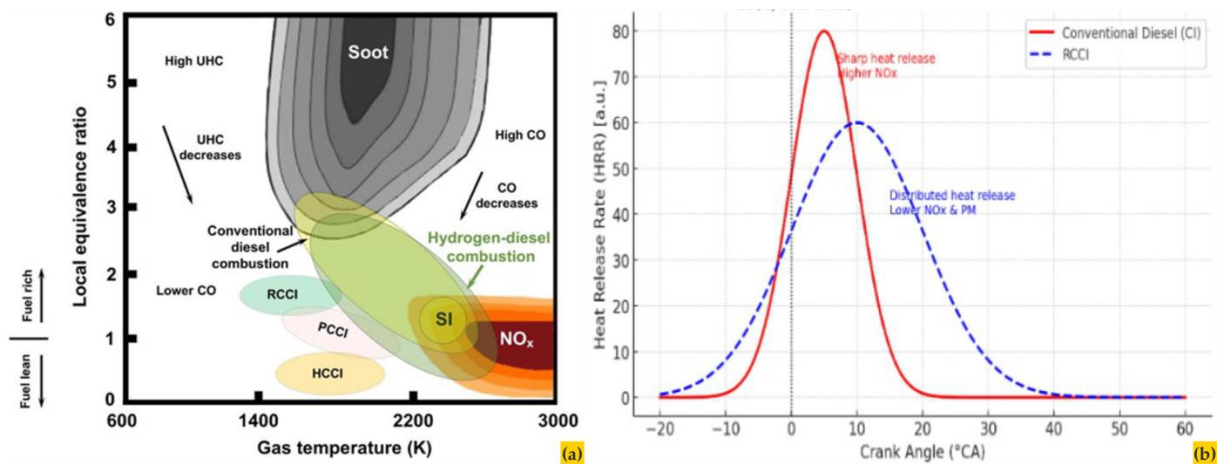


Figure 19. (a) Areas of NOx and soot formation in conventional diesel combustion at low temperature and the changes observed in the presence of H₂. PCCI, HCCI, RCCI, SI; (b) CI and RCCI heat dissipation modes [66]

combustion processes at lower temperatures offers the potential to reduce the emissions of NOx and soot from diesel engines [132]. The extant literature delineates a diverse array of low-temperature combustion methodologies, encompassing HCCI, PCCI, and RCCI, all of which have undergone rigorous investigation and analysis [59], [66]. The RCCI technique has attracted considerable attention due to its ability to function across a wide range of engine loads while achieving near-zero emissions of NOx and soot (as illustrated in Figure 19a) through the adjustment of fuel ratios and modifications in injection strategies [73], [133]. In RCCI engines, the formation of reactivity within the combustion chamber is meticulously controlled, thus influencing the progression of combustion [80], [134]. Within this dual-fuel combustion framework, at least two fuels with differing reactivity characteristics are utilized [19], [135].

Figure 19b the main difference between the conventional diesel cycle (CI) and the RCCI cycle lies in the combustion control method and the

type of fuel used. In a CI, the heat release process occurs very quickly and is concentrated around the top dead center, resulting in high pressure and temperature peaks that contribute to increased NOx emissions. In contrast, in an RCCI engine, heat release occurs more evenly and is distributed more widely before and after Top Dead Center (TDC), resulting in a gentler heat release curve. This more controlled energy distribution not only reduces NOx and PM emissions, but also increases thermal efficiency and creates cleaner and more stable combustion characteristics.

Particulate Matter (PM) encompasses carbonaceous materials that emerge from the incomplete combustion process of hydrocarbon fuels [19]. PM represents a complex pollutant that comprises both soluble and insoluble substances, in addition to dry fractions [136]. Soot, classified as an insoluble material, constitutes a significant portion of PM, surpassing 50%. The remaining constituents of PM, which make up approximately 50%, consist of unburned hydrocarbons, partially combusted hydrocarbons,

unburned or partially combusted lubricating oils, wear debris from engines, and sulfates originating from fuel [66], [73], [137]. The mitigation of PM emissions may be feasible through the enrichment of hydrogen, owing to the absence of carbon in hydrogen and the resulting decrease in the diesel fuel injection rate [93]. The integration of hydrogen into diesel fuel can increase the flame temperature and improve the combustion of hydrocarbons, thereby limiting the generation of PM [59]. The replacement of diesel fuel with hydrogen could yield a more uniform air-fuel mixture, which would diminish the presence of fuel-rich pockets and concurrently reduce PM emissions [4], [138], [139].

Furthermore, empirical data indicate that the incorporation of hydrogen may facilitate a diminishment in both particle dimension and number concentration, attributable to its suppressive influence on the hydrogen abstraction and C_2H_2 addition pathways [58]. Moreover, the coalescence of diminutive aggregate particles into more substantial clusters could plausibly be mitigated through the introduction of hydrogen into ultra-low sulfur diesel, as evidenced by the Transmission Electron Microscopy (TEM) images depicted in Figure 20 [140]. The integration of hydrogen may also modify the nanostructure of the primary particles expelled from the diesel engine. The High-Resolution Transmission Electron Microscopy (HRTEM) images illustrated in Figure 21. reveal a significant transition from the 'turbostratic interlayer' configuration to an 'onion-like' structure following the introduction of hydrogen into diesel fuel at engine speeds of 1200 and 1800 rpm under a 30% engine load. Additionally, the "shell-core" structure may undergo a transformation into a "shell-amorphous" arrangement through the infusion of hydrogen into diesel fuel at 1200 and 1800 rpm under conditions of 70% full-load operation.

The addition of hydrogen to ultra-low sulfur diesel in various engine load [140]. In the context of the emissions challenge, it is consistent with the literature reviewed and researched that RCCI engines utilizing a hydrogen-diesel fuel blend exhibit significant potential for mitigating detrimental emissions including CO_2 , CO, and particulate matter [99]. Nevertheless, the systematic and precise oversight of engine

operational parameters, encompassing fuel ratio, injection timing, and EGR implementation, is crucial for reducing elevations in NO_x emissions, particularly under conditions of elevated engine loads [115]. Modifications in innovative methodologies and engine management strategies may be requisite to fully harness the advantages of this technology in practical applications that could enhance operational efficiency [140], [141].

3.1.3. Clean Combustion at ICE (Induced RCCI)

The field of clean combustion within internal combustion engines (ICE) has emerged as a crucial area of scholarly inquiry in light of global initiatives aimed at reducing greenhouse gas emissions and fulfilling carbon neutrality goals [142]. Among several strategies available, Reactivity Controlled Compression Ignition (RCCI)

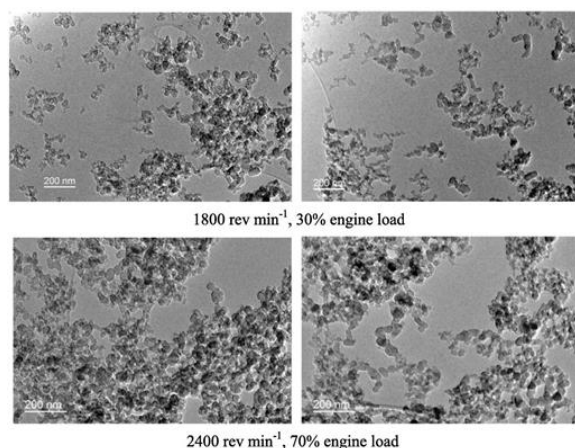


Figure 20. Example of test result images of the right part of TEM and the left part of PM [140]

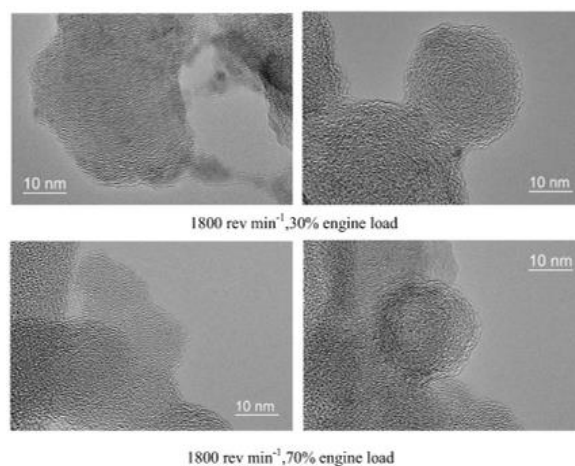


Figure 21. Example of test result images of the right part of HRTEM and the left part of PM with the addition of hydrogen to ultra-low sulfur diesel in various engine loads [140]

presents a promising low-temperature combustion (LTC) methodology that facilitates precise regulation over ignition timing and combustion phasing through the utilization of two fuels characterized by differing reactivity levels [80]. Notably, the amalgamation of hydrogen as the low reactivity fuel (LRF) with diesel as the high reactivity fuel (HRF) has demonstrated considerable efficacy in diminishing detrimental emissions, particularly those associated with carbon-based pollutants [48].

Figure 22 illustrates the impact of hydrogen supplementation on exhaust emissions in an internal combustion (CI) engine operating under a dual fuel paradigm (hydrogen-diesel). The findings indicate that augmenting the hydrogen proportion within the fuel amalgamation exerts a beneficial effect on the cleanliness of the combustion process [143]. The emissions of carbon monoxide (CO) experienced a marked decline attributable to the rapid and efficient combustion characteristics inherent to hydrogen, thereby mitigating instances of incomplete combustion [144]. A similar reduction was observed in carbon dioxide (CO₂) emissions, which diminished as hydrogen lacks carbon constituents; thus, an increased energy contribution from hydrogen correlates with a decreased production of CO₂ [145].

Furthermore, the emissions of particulate matter were significantly diminished due to the fact that hydrogen combustion does not yield soot, rendering this fuel combination particularly advantageous for the alleviation of particulate pollution. Conversely, the escalated utilization of hydrogen also resulted in an increase in nitrogen oxide (NO_x) emissions [146]. This phenomenon can be attributed to the elevated combustion temperatures that arise from the rapid combustion of hydrogen, which promotes the reaction responsible for NO_x formation [105]. These advancements underscore that while hydrogen facilitates the attainment of cleaner combustion with respect to carbon and particulate emissions, supplementary strategies remain imperative for the regulation of NO_x emissions, including the implementation of Exhaust Gas Recirculation (EGR) systems or water injection techniques. In summary, the integration of hydrogen into diesel engines presents considerable prospects for advancing environmentally sustainable engine

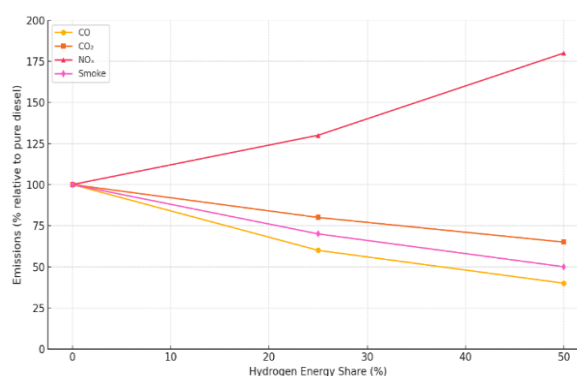


Figure 22. Effect of dual fuel hydrogen-diesel on emissions in clean combustion [145]

technologies, even though emission management for high temperature processes is needed [75], [147].

4. Conclusion and Recommendations

The incorporation of hydrogen as an auxiliary fuel in dual-fuel compression ignition engines employing the reactivity controlled compression ignition (RCCI) presents a viable solution to the prevalent issues pertaining to energy efficiency and the minimization of emissions. Hydrogen, recognized for its environmentally favorable combustion traits and its prospects for sustainable energy, has been empirically validated to diminish the consumption of diesel fuel and the output of carbon dioxide (CO₂). Furthermore, the amalgamation of hydrogen has the potential to enhance the thermal efficiency of the engine owing to its rapid combustion characteristics and elevated specific energy content. Overall, hydrogen-powered dual-fuel Diesel/RCCI engines exhibit significant potential to facilitate the transition towards cleaner and more efficient energy technologies. As research and technological innovation advance, it is foreseen that present technical and economic hindrances will be resolved in the foreseeable future. Nevertheless, the deployment of this technology is accompanied by challenges, including heightened emissions, potential knocking phenomena, and the necessity for an exacting fuel control system, all of which represent obstacles that must be addressed. Recent studies suggest that supplementary technologies, such as Exhaust Gas Recirculation (EGR) and more sophisticated hydrogen injection systems, may offer viable strategies to alleviate these challenges.

Recommendations in future work or research should focus on finding the right fuel mixture, operating parameters, and engine adjustments according to the feasibility test standards by considering technical, thermodynamic, economic, and environmental issues with the final output of clean combustion with increased performance. To accomplish this objective, it is necessary to stimulate collective initiatives among researchers, industry actors, and policymakers to propel and apply this hydrogen-integrated RCCI technology in a sustainable and effective manner.

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Author's Declaration

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

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